The effect of gap openings on soil reinforcement in two conifer stands in northern Italy

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Abstract

Gap-oriented forestry is a subject that is gaining interest worldwide as a compromise between economic and operational requirements on the one hand and environmental and safety concerns on the other. In principle, the approach mimics the effects of fine-scale natural disturbance while avoiding the threats of soil degradation and instability associated with large clearcuts, but at the same time, it does not limit the productivity associated with single-tree selection.

Despite this interest, studies of the real effects of gap-oriented forestry are still limited, particularly those dealing with its impact on slope stability. This paper provides quantitative results about the slope stability of two mixed-conifer stands subjected to gap management in the Italian Central Alps that were monitored for five years after felling.

The results showed that root decay, both in strength and density, further reduces additional root cohesion by approximately 60% in the first two years after felling and by another 20% in the third year; it completely vanishes by the fifth year. The observed reduction in root reinforcement values has dramatic consequences for slope stability. In fact:

- In undisturbed conditions, the contribution of forest root systems guarantees a very low probability of instability (approximately 10% for a factor of safety of less than 1 as well as for steep slopes and high levels of saturation).
- After only two years, the probability of instability dramatically increases for gentle slopes and low levels of saturation. We estimated a 50% probability of a factor of safety less than 1 when steepness was greater than 36–38° and soil saturation was 25% and when steepness was greater than 24–26° and soil saturation was 75%.
- The probability of instability is highest five years after felling when the contribution of the root system has vanished. The probability of failure exceeded 50% when steepness was greater than 25–28° and saturation was 25%, and the slopes were practically unstable when saturation was 75%.
- At the point when the contribution of the root system to slope stability was null, the regeneration process was still too undeveloped to contribute to soil reinforcement in any way

These results suggest that although the gap-oriented approach is, in principle, more conservative than large clearcuts, the pace of natural regeneration could be slower than the process of root decay, so instability could occur, especially where local slopes exceed 25° and soils are frequently saturated.

1. Introduction

Gap-oriented forestry is a regeneration system that leads to heterogeneous forest structures, which promote multi-functional forest management (York et al., 2007, Lhotka et al., 2013). This practice can be incorporated into the group selection method as it consists of creating small canopy openings (generally less than 1000–1500 m2) by cutting groups of dominant trees, thus mimicking the effects of fine-scale natural disturbance and regeneration processes (Smith et al., 1997, Coates and Burton, 1997). Such an approach reduces both the environmental degradation associated with large clearcuts and the limited

productivity associated with single-tree selection (Bliss, 2000, Mercurio and Spinelli, 2012, Lhotka et al., 2013).

Gap-oriented forestry has been successfully implemented to manage a large variety of forest stands worldwide, including mangrove forests in the Philippines (Walters, 2005), eucalyptus forests in Australia (Van Der Meer et al., 1999), Sierran mixed-conifer forests in California (York et al., 2007) and conifer forests in the Italian Apennines (Albanesi et al., 2008, Mercurio and Spinelli, 2012). The optimal gap size varies depending on the light requirements of the forest species, although this system is considered to be particularly appropriate for stands dominated by shade-tolerant trees (e.g., Abies, Picea and Fagus species) (McCarthy, 2001, Nocentini, 2009, Nagel et al., 2010, Cater et al., 2014). The gap-oriented approach has also been proposed as a way to combine stand renewal with other forest management objectives, such as ecological restoration (Storer et al., 2001) and biodiversity conservation (Hamer et al., 2003, Lahde et al., 1999, Schütz, 1999, Walters, 2005, USDA, 1995), and several studies have explored the influence of gap distribution and size on the natural regeneration dynamics in different types of managed forests (Gray and Spies, 1996, Coates, 2000, Coates, 2002, Malcolm et al., 2001, Diaci, 2002, Gray et al., 2002, Gagnon et al., 2003, Zhu et al., 2003, Albanesi et al., 2008). Furthermore, the effectiveness of gap-oriented silviculture as a tool for the restoration of age diversity and "naturalness" in artificial or repeatedly harvested, even-aged stands has also been investigated (Malcolm et al., 2001, Seymour, 2005, Albanesi et al., 2008). Gap-oriented forestry has also been applied in Italy in recent decades for the sustainable management of even-aged stands of silver fir and Norway spruce, some of which have been previously subjected to clearcutting (Ciancio et al., 1985, Mercurio and Spinelli, 2012). Most of these forests grow in mountain sites and play an important role in slope protection. Nevertheless, scientific information about the effects of gap openings on the contribution of tree roots to slope stability remain scarce (Ammann et al., 2009), particularly the quantification of these effects.

Due to the small area that is disturbed, gap-oriented forestry should have advantages in terms of soil protection compared to other forest management systems. In fact, many experimental studies have stressed the negative effects of clearcutting on soil erosion and landslide frequency in steep forest slopes (Swanson and Dyrness, 1975, Wu and Swanston, 1980, Johnson et al., 2000, Dhakal and Sidle, 2003), but Dhakal and Sidle (2003) observed a reduction in landslide occurrence and volume in forested areas where partial cutting had replaced clearcutting. Actually, it is well known that forests promote soil reinforcement, mainly through the roots that permeate the soil, by affecting the hydrological processes and mechanical behavior of hillslopes. Much of the existing literature is focused on the latter, which is generally described in terms of additional root cohesion and is recognized as one of the major factors determining the stability of vegetated slopes (Zhou et al., 1998, Roering et al., 2003, Schmidt et al., 2001, Schwarz et al., 2010b). As a gap opening progressively modifies the factors on which additional root cohesion depends (i.e., the root density, size distribution and tensile strength inside the cut area; Vergani et al., 2014a), knowing the dynamics of root features following gap openings in forest stands is of great importance.

Recently, Cordonnier et al. (2008) proposed small gap forestry in stands of Norway spruce in the Alps, and Berger and Rey (2004), working in the Southern Alps, recommended opening gaps with a maximum size of 300 m2 for the regeneration of Austrian black pine stands in sites that are highly subjected to soil erosion. However, scientific information on the relationships between gap forestry and slope protection remain scarce (Ammann et al., 2009), particularly from a quantitative point of view.

This paper aims to increase the understanding of the practice of gap-oriented forestry by providing new quantitative data on root cohesion dynamics within gaps, and the related change in slope stability, following felling in two mixed-conifer stands in the Italian Central Alps. Root density, size distribution and tensile strength, as well as the natural regeneration of forest species, were monitored for five years in two patches after gap-cutting to estimate the resulting changes in additional cohesion values.

The results were incorporated into a probabilistic slope stability model capable of considering forest presence to provide guidance to forest managers on the possible effects of gap-cutting on slope stability.

2. Materials and methods

2.1. The study sites

We selected two study sites with similar characteristics where, in the last decade, gap-cutting has been introduced as a forest management system in place of single-tree selection cutting. At each site, two stands, an opened gap and an adjacent portion of undisturbed stand (control), were monitored for five years. The sites are located within the municipalities of Cusio and Averara (Brembana Valley, Central Alps, Northern Italy, Fig. 1) in the subalpine catchment of the Brembo River.

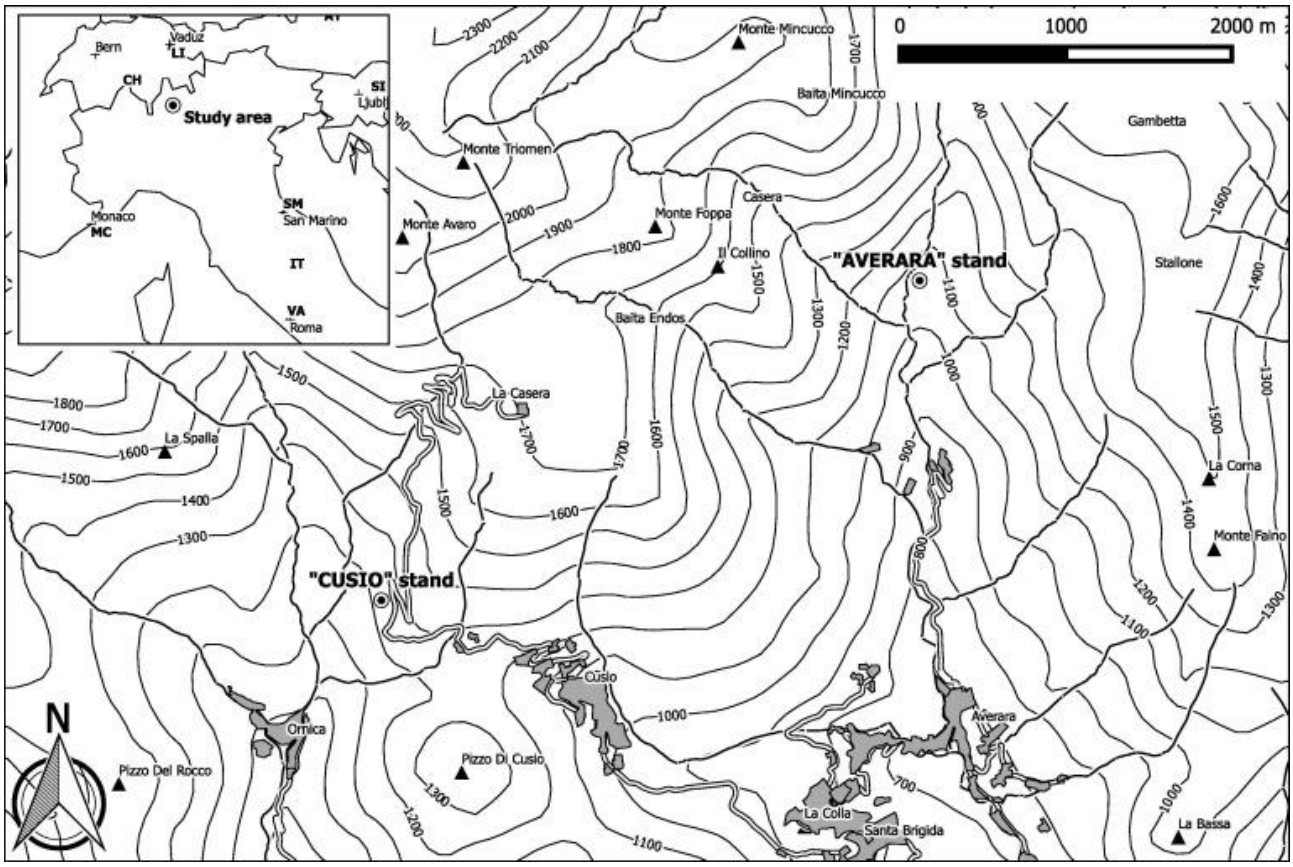

Fig. 1. The study sites are located in the subalpine catchment of the Brembo River in Lombardy, Northern Italy.

The study area falls within the Mesalpic Forest Region (Del Favero, 2002), which is characterized by a mean annual rainfall of 1400 mm, with two peaks in the autumn and spring, and a mean annual temperature of 7.2 °C.

The bedrock belongs to the Collio Formation, a semi-permeable siliceous substrate that is a group of sandstones and characterized by high weathering and soils originating from siliceous rocks. According to the WRB classification (World Reference Base for Soil Resources; IUSS Working Group WRB, 2006), the soil in Cusio is umbrisol and is characterized by a silty matrix with low permeability, “moder” type organic matter and low base saturation (Soil map of the Lombardy Region). In contrast, the soil in Averara is classified as cambisol with a sandy loam texture. Cobbles and stones are abundant in the deeper layers in both sites.

2.2. Stand characteristics

The forest type is the same at both sites, a mixed forest of Abies alba (predominant species: 60–70%) and Picea abies (20–30%) with occasional broadleaf species (Fagus sylvatica in Cusio and F. sylvatica and Castanea sativa in Averara), which is classified by the Italian system as a typical silver fir wood with silicatious soils (Del Favero, 2002). The age of the stands in the logged areas was between 80 and 120 years at Cusio and between 90 and 120 years at Averara. The elevation of the stands is 1200 m and 1000 m a.s.l. at Cusio and Averara, respectively, and in both cases, the stands are located on the middle of the slope. Both sites had a southwest aspect, and the angle of the slope was between 24° and 27° at Cusio and between 30° and 35° at Averara.

In each of the undisturbed control stands, which were located adjacent to the gaps, a circular sampling plot was established with a 15-m radius. Stem diameter at breast height was measured for all of the trees in the plots along with some representative heights (Fig. 2). The basal area of the living stand was 30.36 m2/ha at Cusio and 33.26 m2/ha at Averara, whereas the mean height and diameter were 31 m and 0.31 m and 30 m and 0.33 m, respectively.

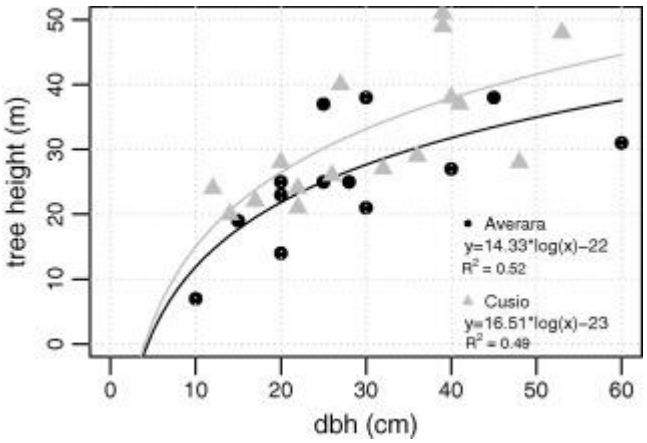

Fig. 2. Height curves of the undisturbed forest stand in Averara and Cusio. Root sampling.

Gap-cutting was carried out at Cusio in the summer of 2009 with a harvested area of approximately 1000 m2 and at Averara in the winter of 2010 with a harvested area of approximately 600 m2. All of the trees within the gap were removed.

Within each gap, we performed field surveys and sampling at the center for four years: the summers of 2010, 2011, 2012 and 2014, and we selected sampling points where only conifer trees were present. In

2010, we also monitored the adjacent, undisturbed stand in both sites to provide reference conditions. Therefore, we were able to collect data under the following conditions: undisturbed (0_months), 12_months, 24_months, 36_months and 60_months after felling at Cusio, and undisturbed (0_months), 6_months, 18_months, 30_months and 54_months after felling at Averara. The Cusio data were taken from Vergani et al. (2014a), except for 60_months.

At every time-step, a 0.9-m long trench was dug to the depth at which roots were no longer present, allowing for the analysis of the root density in the soil profiles and root sampling for tensile resistance tests. The depth of the trenches varied between 0.50 and 1.30 m (Table 1) depending on the abundance of stones and cobbles, which prevented further excavation, but very few roots can only occasionally be found beneath the depth reached by the trenches. This has been confirmed by several studies showing that roots in northern forests are generally restricted to the upper soil layers with most roots occurring within the first 0.30 to 0.50 m of the soil profile (Persson, 1980, Persson, 1983, Comeau and Kimmins, 1989, Finér et al., 1997, Millikin and Bledsoe, 1999, Püttsepp et al., 2006).

Table 1. Main characteristics of each sample site and each trench at Cusio and Averara. The number and diameters in the gaps refer to the trees and stumps, and the diameters in the undisturbed forest are measured at breast height (∗). The distance refers to that between the trench and stumps (or trees) (x_months = x months after felling).

Time interval	Understorey cover (%)	Understorey species (mean height, cm)	Number of surrounding trees or stumps (*Abies alba*)	Mean diameter (m)	Mean distance (m)	Max distance (m)	Min distance (m)	Depth of trench (m)
Cusio								
0_months	5	*Vaccinium myrtillus* (L.) (15); *Picea abies* regeneration (8)	5	0.30∗	3.2	5.3	2	0.70
12_months	10	*Luzula nivea* (L.) (15); *Rubus* spp. (L.) (40)	4	0.46	3.1	4.9	1	0.90
24_months	50	*Luzula nivea* (20); *Rubus* spp. (50), *Vaccinium myrtillus* (20); *Pteridium aquilinum* (L.) (55)	8	0.50	3.3	5.2	2	1.10
36_months	90	*Luzula nivea* (L.) (20); *Rubus* spp. (L.) (60), *Vaccinium myrtillus* (L.) (20); *Pteridium aquilinum* (L.) (55); *Poa pratensis* (L.) (20)	6	0.57	3.2	5.0	2	0.90
60_months	100	*Luzula nivea* (L.) (20); *Rubus* spp., (L.) (65) *Vaccinium myrtillus* (L.) (20); *Pteridium aquilinum* (L.) (55); *Poa pratensis* (L.) (20)	7	0.45	3.9	6.1	2.2	0.50
Averara								
0_months	<5	Ferns	7	0.30∗	3.2	5.3	2	0.90
6_months	5	*Luzula nivea* (L.) (15); *Rubus* spp. (L.) (40); Ferns (40)	4	0.50	3.2	4.2	2.2	0.80

Time interval	Understorey cover (%)	Understorey species (mean height, cm)	Number of surrounding trees or stumps (*Abies alba*)	Mean diameter (m)	Mean distance (m)	Max distance (m)	Min distance (m)	Depth of trench (m)
18_months	50	*Luzula nivea* (L.) (15–20); *Rubus* spp. (L.) (40–50), Ferns (40–50)	9	0.45	4.7	6.9	2.3	1.30
30_months	90	*Luzula nivea* (L.) (20); *Rubus* spp. (L.) (60); *Poa pratensis* (L.) (20), *Vinca Minor* (L.) (10), *Abies alba* regeneration (10)	7	0.49	3.3	5.5	2.3	0.90
54_months	100	*Luzula nivea* (L.) (20); *Rubus* spp. (L.); *Poa pratensis* (L.), *Vinca Minor* (L.) (10), *Abies alba* regeneration (15)	6					

Trenches were dug in the center of the gaps in the middle of a group of stumps (or living trees in the undisturbed forest), where the level of root reinforcement was likely to be minimal, so estimates were conservative. Due to the destructive nature of the trench method, the sampling points had to be changed each year, but we always choose the same number of stumps with a similar diameter and maintained the same distance between the trench and the stumps.

2.3. Root density estimation

Root density was analyzed in terms of the number of roots per root diameter class by means of the trench wall method (Bohm, 1979, Abernethy and Rutherfurf, 2001, Schmid and Kazda, 2002, Abdi et al., 2010, Douglas et al., 2010) and image analysis (Bischetti et al., 2009, Hales et al., 2009).

Root diameter and position were measured by the manual digitization of each root using GIS software (MapWindow 4.6: www.mapwindow.org). The number of roots per diameter class was determined in increments of 0.10 m in depth, and the diameter classes under consideration were 0–1 mm, 2–5 mm, 5–10 mm, and >10 mm (Genet et al., 2008, Ji et al., 2012). For completeness, roots with diameters <1 mm and >10 mm were also considered in the root analysis even if they were not included in the cohesion calculation, as explained below.

2.4. Root strength

Most of the previous studies of root strength decay considered root tensile stress values (Burroughs and Thomas, 1977, Ziemer and Swanston, 1977, Ziemer, 1981, O'Loughlin and Ziemer, 1982, Ammann et al., 2009), but our study considers root tensile force at rupture, which is the experimentally measured variable, according to several others (Hathaway and Penny, 1975, Ziemer and Swanston, 1977, Nilaweera and Nutalaya, 1999, Schmidt et al., 2001, Kondo et al., 2004, Norris, 2005, Tosi, 2007, Hales et al., 2009, Genet et al., 2011, Vergani et al., 2012). This approach avoids introducing a possible additional source of variance as the tensile stress of the roots is calculated as the ratio between breaking force (N) and root area (mm2), which, in turn, depends on root diameter (Vergani et al., 2012). Roots were collected in both organic and mineral horizons by digging pits in the middle of the study sites between adjacent stumps within the gaps, or between live trees within the undisturbed forest, taking care not to damage them and sampling to cover the entire range of diameters from 1 to 10 mm (as further discussed below). Roots samples were preserved from deterioration in plastic containers filled with a 15% alcohol solution (Meyer and Göttsche, 1971,

Bischetti et al., 2003) until tensile tests were performed following the methodology described by Bischetti et al., 2005, Bischetti et al., 2009, which generally occurred within one month of root collection.

Tensile tests were carried out at a strain rate of 10 mm/min using specially developed clamping devices to avoid root damage at the clamping points (Bischetti et al., 2009), and tensile force was recorded by a load cell (Full Scale, F.S. = 500 N, accuracy = 0.1% of F.S.). Only specimens that broke near the middle of the roots were included in the data to ensure that the rupture was due to the tension and not structural damage to the root or the concentration of stress near the clamps.

Root size was estimated as the average of three values taken with an electronic caliper at three points near the potential breaking point (Abdi et al., 2010, Vergani et al., 2012).

In addition to species-specific differences, it is well known that the tensile resistance of roots is strongly dependent on their size and generally follows a power-law relationship (Ziemer and Swanston, 1977, Nilaweera and Nutalaya, 1999, Kondo et al., 2004, Genet et al., 2010, Abdi et al., 2010, Vergani et al., 2012); over 50 force–diameter values across the whole range in diameters were taken for each site.

2.5. Estimation of soil reinforcement

Additional root cohesion (cr) is commonly estimated using two classes of models (Bischetti et al., 2009, Ji et al., 2012, Mao et al., 2012): the pioneering approach based on the behavior of single fibers by Wu (1976) and Waldron (1977) and the more recent approaches based on bundles of fibers, the Fiber Bundle Model (FBM) (Pollen and Simon, 2005) and the Root Bundle Model (RBM) (Schwarz et al., 2010a).

Due to some limitations, particularly the assumption that the breakage of roots at soil failure is simultaneous, the Wu and Waldron model has generally been abandoned in favor of FBM. On the other hand, the RBM introduced by Schwarz et al. (2010a) provides a more complete description of the root-breaking process by accounting for displacement, but it requires the calibration of a higher number of parameters.

The FBM is an approach that was introduced in the field of physics several decades ago (Daniels, 1945) and adopted by Pollen and Simon (2005) to account for the progressive failure of roots according to their individual tensile resistance, which in turn, depends on both their diameter and ultimate stress at failure (Ji et al., 2012, Vergani et al., 2014a). Since its introduction, the FBM has been used extensively to estimate root reinforcement (Bischetti et al., 2009, Hales et al., 2009, Mickovski et al., 2009, Mao et al., 2012, Ji et al., 2012, Vergani et al., 2014a) by adopting different hypotheses about the load-sharing criteria following the rupture of the roots (Mao et al., 2012, Ji et al., 2012, Vergani et al., 2014a).

In this study, the FBM has been implemented under the static fiber bundle approach and equal load sharing, as described in detail in Bischetti et al. (2009) and Ji et al. (2012).

The additional root cohesion value at depth Z, cr, incorporates both the resistance due to those roots crossing the basal shear surface, cbas, and the resistance due to those roots intersecting the vertical plane at the detachment scarp, clat (Riestenberg and Sovonik-Dunford, 1983, Terwillinger and Waldron, 1991, Schmidt et al., 2001, Keim and Skaugset, 2003, Roering et al., 2003, Dietrich et al., 2003, Casadei et al., 2003, Schwarz et al., 2010a). In the case of small-volume landslides in shallow forested soils, the lateral root reinforcement is important for landslides with areas of up to 1000 m2 (Schwarz et al., 2010b).

For each case, the distribution of cr at each trench was calculated for roots in the range of 1–10 mm because they are generally considered as having the greatest influence on soil stabilization (Waldron, 1977, Stokes et al., 2009, Finér et al., 2011, Tosi, 2007, Genet et al., 2010, Abdi et al., 2010, Bischetti et al., 2009), even though some authors have highlighted the importance of the contribution of roots larger than 10 cm in diameter (Vergani et al., 2014b, Reubens et al., 2007). However, laboratory testing of the mechanical

properties of roots larger than 10 mm in diameter and their distribution within the soil is extremely challenging, so in this study, the consideration of roots with diameters up to 10 mm will provide conservative values.

2.6. Statistical analyses

The relationship between root tensile force F (N) and root diameter d (mm) was obtained by regression analysis of the log-transformed values of F and d. Goodness-of-fit was evaluated through the coefficient of determination (R2) and the coefficient of significance (p-value) from Fisher's test at a level of significance of 0.01. Fisher's test was also applied to linear regressions obtained from the log-transformed values of F and d.

Due to the dependence of tensile force and strength from diameter, an ANCOVA is frequently adopted when comparing values obtained from different species, sites, etc. (Genet et al., 2005, Genet et al., 2010, Bischetti et al., 2009, Ji et al., 2012, Vergani et al., 2012).

A multiple regression was performed to compare the force values of roots coming from different conditions with diameter as a covariate (Soliani, 2005). The logarithm of force was used as the dependent variable; the logarithm of diameter was the independent variable, and the n conditions were represented by n − 1 dummy independent variables. Each dummy variable assumes the value of 1 for the force values belonging to the condition under consideration and 0 for the force values in all other cases. The values belonging to the undisturbed condition are therefore identified by having a value of zero for each independent dummy variable.

The significance of the whole model was evaluated by Fisher's test and the adjusted coefficient of determination (adjusted R2), whereas the significance of each independent variable was evaluated with a Student's t-test and partial Fisher's test with a 0.05 level of significance. The force values of a condition can be considered significantly different from the force values of the reference case (undisturbed forest) if the corresponding dummy variable is significant.

The requirements of normality and the independence of residuals were verified through Kolmogorov–Smirnov and Breush–Godfrey tests at the 0.05 level of significance. All of the statistical analyses were performed using program R (http://www.r-project.org/).

2.7. Regeneration sampling

Within each gap selected for this study, a survey of the natural regeneration of tree species was performed by walking along the N–S and E–W axes. Thirteen circular plots (3 m in radius) were established in Cusio (1 central plot and 3 plots along each the four radial directions) and 17 in Averara (1 central plot, 3 plots along the N–S directions and 5 plots along E–W directions to account for the elliptical shape of the gap). The total area surveyed was approximately 91.8 and 120.1 m2 at Cusio and Averara, respectively. The number and height of the naturally regenerated saplings taller than 2 cm were recorded along with species and height, and age and vegetative condition were also evaluated for conifer seedlings. Plantlet age was estimated through a whorl count, and each individual was assigned to one of the following health categories: good (seedlings in good vegetative condition without external signs of disease or damage); intermediate (plantlets with minor signs of disease or damage); poor (seedlings with poor growth and/or marked signs of disease or damage).

2.8. Evaluation of slope stability

Shallow landslides usually involve the colluvial layer of the earth mantle (Milledge et al., 2014) and can be modeled as a rigid volume of thin soil sliding on planar shear surfaces (Casadei et al., 2003, Dietrich et al., 2008). In forest hillslopes, additional root cohesion must be accounted for, but roots penetrating the basal

sliding surface can rarely be found. On the other hand, it is common to observe many broken roots along the lateral surface of a landslide scarp (Riestenberg and Sovonik-Dunford, 1983, Burroughs, 1984, Hammond et al., 1992, Roering et al., 2003, Schmidt et al., 2001, Schwarz et al., 2010b).

Shallow landslides occurring on forested hillslopes can be schematically represented by the application of limit equilibrium theory and the stability of a hillslope as expressed by the factor of safety, FS, which considers the presence of roots on the basal and lateral surfaces (Burroughs, 1984, Dietrich et al., 2008, Schmidt et al., 2001, Roering et al., 2003) and neglects lateral earth pressure due to its minor contribution (Dietrich et al., 2008) as follows:

$$\mathrm{FoS} = \frac{S}{T} \tag{1}$$

where S is the resisting forces and T is the shear force.

The resisting forces, S, can be evaluated according to the Mohr Coulomb failure criteria as:

$$S = C_b + C_l + [(W - U + Q)\,cos\ \alpha]\,tan\ \phi' \tag{2}$$

where W is the weight of the volume of soil under consideration ($W = A_b D\gamma_s$, where A_b is the basal area of the sliding volume; D is the average depth of the soil mantle, and γs unit weight of dry soil); U is the pore pressure ($U = A_b D_w \gamma w$, where D_w is the average depth of the water table, and γ_w is the unit weight of water); Q is the tree surcharge term (Q = Abqo, where qo is the tree surcharge per unit area); α is the slope steepness, φ′ is the effective internal friction angle, and C_b and C_l are the cohesion terms acting on the basal and lateral surfaces, respectively.

The shear force, T, is assumed to be equal to the tangential component of the sliding volume and the tree surcharge:

$$T = (A_b D\gamma_s + A_b D_w \gamma_{sat} + A_b q_o)\,sin\ \alpha \tag{3}$$

where γ_{sat} is the unit weight of saturated soil.

FS can then be written as:

$$\mathrm{FoS} = \frac{A_b(c_s + c_b) + A_l(c_s + c_l) + [A_b(D\gamma_s - D_w\gamma_w + q_o)\,cos\ \alpha]\,tan\ \phi'}{A_b(D\gamma_s + D_w\gamma_{sat} + q_o)\,sin\ \alpha} \tag{4}$$

where c_s is the soil cohesion; A_b and A_l are the basal and the lateral surface areas, respectively, and c_b and c_l are the contribution of the plant roots along the basal and lateral surfaces.

According to Casadei et al. (2003), Eq. (4) can be rearranged by dividing by A_b:

$$\mathrm{FS} = \frac{S}{T} = \frac{(D\gamma_s - D_w\gamma_w + q_o)\,cos\ \alpha\,tan\ \phi' + c_s + c_b + \frac{A_l}{A_b}c_l}{(D\gamma_s + D_w\gamma_{sat} + q_o)\,sin\ \alpha} \tag{5}$$

As A_l can be estimated as the product of the scarp perimeter and the scarp depth (D), the ratio A_l/A_b can be considered a measure of the plan view of the landslide. The volume and geometric properties of shallow landslides have been the object of several studies based on field-mapping inventories have shown great variability. However, Milledge et al. (2014) recently analyzed six large inventories and found that the majority of shallow landslides have a depth of less than 1 m, an area on the order of 100 m^2 and a length/width (L/W) ratio within a very narrow range, approximately 2.

Assuming D = 1 m, then for many landslide geometries, the ratio A_l/A_b can be approximated to W/L and its value to 0.5 (Milledge et al., 2014).

Because most of these parameters are affected by natural variability, Eq. (5) was used within a Monte Carlo procedure (Hammond et al., 1992). We then calculated the probability of failure, P(FS < 1) using different values as follows: unit soil density between 488 and 1800 kg/m^3 (De Vos et al., 2005), saturated soil density estimated assuming 40% of the voids are completely filled with water, a friction angle between 29° and 32° and between 32° and 35° for Cusio and Averara, respectively (Hammond et al., 1992). All of the parameters were assumed to be uniformly distributed. Soil cohesion along the sliding surface was set to zero, and tree surcharge, which has a small effect on slope stability analysis (Hammond et al., 1992, Bathurst et al., 2010), was kept at a constant value of 275 N/m2 based on the average values reported for each species in the Lombardy region (Del Favero, 2002). Slope angle was altered from 20° to 50° to account for variations in steepness and three different saturation conditions (25%, 50% and 75%) at different positions along the hillslope or different topographic features; in forest soils, water accumulates downslope and in convergent topography. Finally, three additional root cohesion scenarios were considered: the undisturbed condition, the 2–3 year after cutting condition and the decayed condition.

Each Monte Carlo run was characterized by a total of 1000 repetitions (Hammond et al., 1992), and each had the probability of an FS less than 1 (instability condition). To mitigate the effect of the random selection procedure, runs were repeated 1000 times (note that Hammond et al. (1992) suggested only 2–3 runs), and the resulting failure probability values were averaged and analyzed.

3. Results

3.1. Root density

In Cusio, a general trend in the total number of roots is evident; they remain rather constant for the first three years after felling and then abruptly decrease and become completely degraded after 60 months. The total number of roots per trench was 352, 309, 296, 113 and null for the conditions at 0_months, 12_months, 24_months, 36_months and 60_months, respectively (Table 2 and Vergani et al., 2014a). This trend was confirmed in Averara, where the total number of roots per trench was 203, 224, 220, 209 and null for 0_months, 6_months, 18_months, 30_months, and 54_months, respectively (Table 3).

Table 2. Number of roots in each diameter class under each condition at the Cusio sample site.

Time interval	Total number of roots	Diameter class (mm)	Number of roots	% of total
		0.5–1	175	49.7
		1–2	115	32.7
0_months	352	2–5	52	14.8
		5–10	10	2.8
		⩾10	0	0.0

Time interval	Total number of roots	Diameter class (mm)	Number of roots	% of total
		0.5–1	153	51.7
		1–2	95	32.1
12_months	296	2–5	37	12.5
		5–10	7	2.4
		⩾10	4	1.4
		0.5–1	161	52.1
		1–2	96	31.1
24_months	309	2–5	40	12.9
		5–10	7	2.3
		⩾10	5	1.6
		0.5–1	19	16.8
		1–2	32	28.3
36_months	113.0	2–5	2	1.8
		5–10	2	1.8

Table 3. Number of roots in each diameter class under each condition at the Averara sample site.

Condition	Total number of roots	Diameter class (mm)	Number of roots	% of total
0_months	203	0.5–1	100	49.3
		1–2	76	37.4
		2–5	22	10.8
		5–10	5	2.5
		⩾10	0	0.0
6_months	224	0.5–1	91	40.6
		1–2	96	42.9
		2–5	31	13.8
		5–10	4	1.8
		⩾10	2	0.9
18_months	220	0.5–1	112	50.9
		1–2	85	38.6
		2–5	19	8.6
		5–10	3	1.4
		⩾10	1	0.5
30_months	209	0.5–1	38	18.2
		1–2	110	52.6
		2–5	50	23.9
		5–10	8	3.8
		⩾10	3	1.4

According to Silver and Miya, 2001, Stokes et al., 2009, roots with diameters ⩽2 mm can be classified as fine roots, and roots with diameters >2 mm are thin roots.

Fine roots were the most common size class in all of the conditions at both sites despite the drastic reduction after 30–36 months and the almost complete degradation after 54–60 months (see Vergani et al., 2014a and Fig. 3).

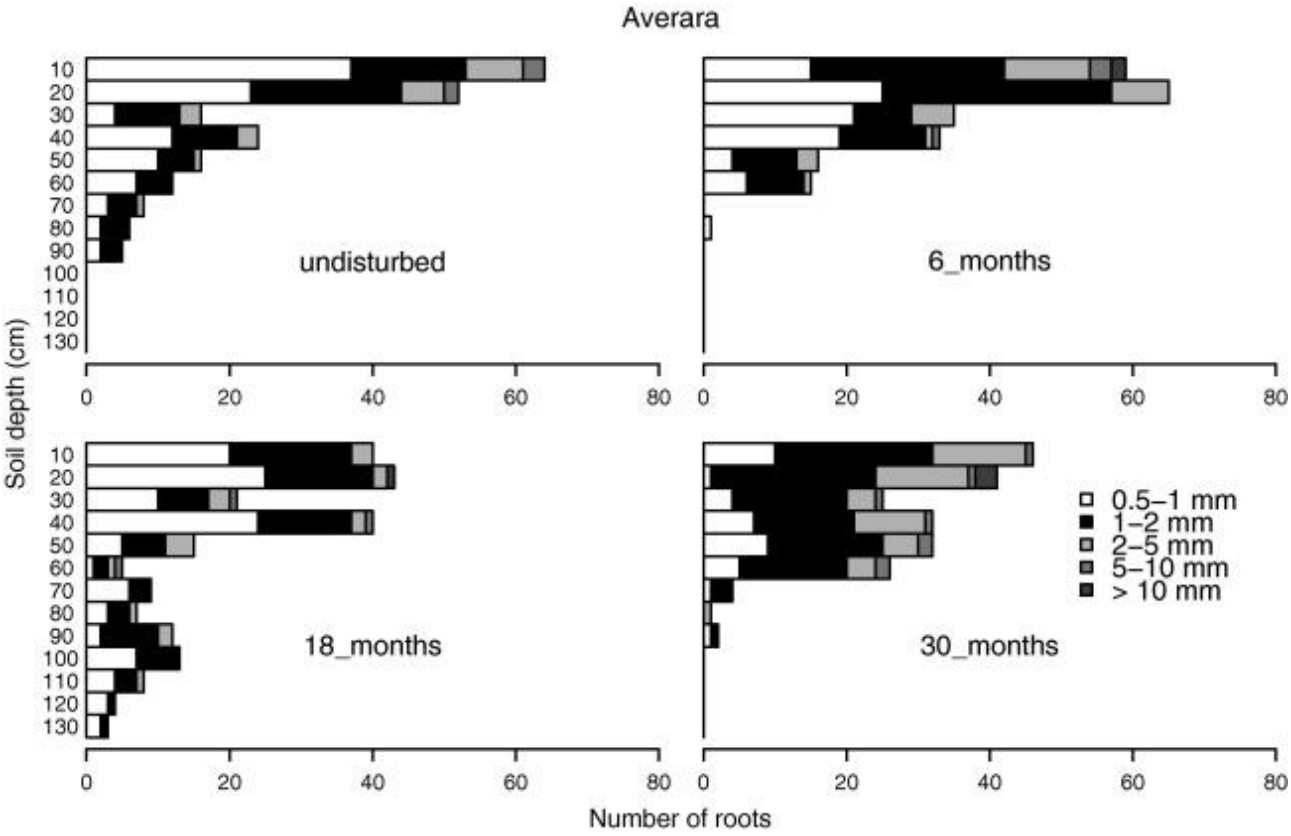

Fig. 3. Root distribution with depth in the Cusio (a) and Averara (b) sample sites.

Under undisturbed conditions, the predominant root diameter class was <1 mm at each depth at both sites (approximately 50%; Tables 2 and 3) followed by the 1–2 mm class (approximately 30%), which tended to prevail after the second year (50%) in all of the layers. For thin roots, the most-represented diameter class at all depths and times was 2–5 mm, whereas the presence of 5–10 mm and >10 mm roots was rare. Due to the small number of thin roots, it was difficult to detect any trend (Vergani et al., 2014a and Table 2).

After 54 and 60 months, the remaining roots were scarce and fully degraded, and the decrease in the density of roots with depth was evident at all time steps (Fig. 3).

3.2. Root tensile force

The number of successful root tensile tests carried out for each condition in the two study sites ranged between 46 and 60 and considered root diameters ranging between approximately 0.5 mm and approximately 9 mm. Despite the care taken to collect a sample with a uniform distribution of root size traits, the diameter distributions of the tested roots were not exactly the same, especially in terms of coarse roots. At both sites, the share of coarse roots increased with time after cutting, and while this could affect mean breaking force values, it has no relevance when statistically robust strength–diameter relationships are developed, as in this study.

As has already been found by several authors (Ziemer and Swanston, 1977, Nilaweera and Nutalaya, 1999, Kondo et al., 2004, Genet et al., 2010, Abdi et al., 2010, Vergani et al., 2012), force values at rupture were related to root diameter through a power-law relationship (Fig. 4). Such relationships were highly significant in all cases ($p < 0.001$) with R2 values greater than 60%, except for Averara after 30 months (Table 4).

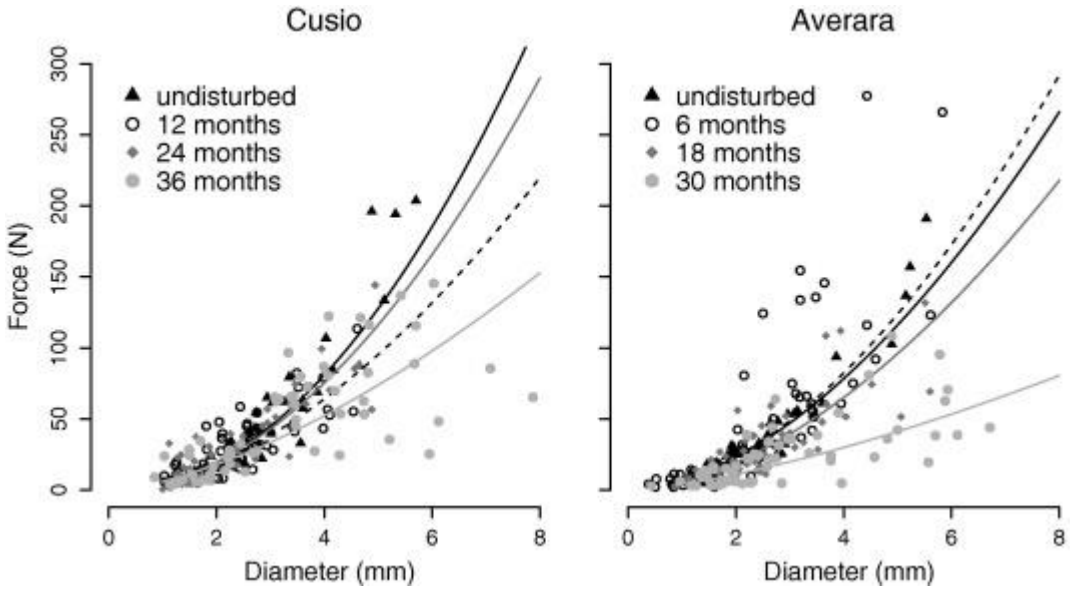

Fig. 4. Force at rupture decreases with time after felling before disappearing after five years. Force values progressively spread through a power law relationship with the live roots (Cusio data taken from Vergani et al., 2014a).

Table 4. Coefficients and statistical parameters of power regressions between tensile force at rupture and root diameter $F = ad^b$.

Time interval	***a***	***b***	***p***	R^2	**SE**
Cusio					
0_months	4.76	2.04	<0.001	0.9	0.27
12_months	5.44	1.78	<0.001	0.62	0.51
24_months	5.08	1.95	<0.001	0.64	0.66
36_months	6.14	1.55	<0.001	0.65	0.60
Averara					
0_months	6.80	1.76	<0.001	0.91	0.24
6_months	6.57	1.83	<0.001	0.74	0.68
18_months	5.82	1.74	<0.001	0.65	0.52
30_months	4.13	1.43	<0.001	0.55	0.68

It can be observed both visually and from the standard error values that the variance in the data progressively increased after felling, possibly due to an increasing number of deteriorated roots; moreover, average root strength decreased with time. After 60 and 54 months from the cuttings at Cusio and Averara, respectively, root strength was impossible to measure as the very few roots found within the soil crumbled after sampling (Fig. 5).

Fig. 5. Roots sampled in the fifth year are weak and mostly deteriorated.

In both cases, the adopted multiple regression model was highly significant ($p < 0.001$) and explained the variability in the force data quite well (adjusted R2 = 0.69 and 0.70 at Cusio and Averara, respectively). As expected, diameter was proven to be highly significant as an explanatory variable in both cases, whereas time-lag variables were not always significant. In particular, time-lag 1 (related to the condition at 12_months) and time-lag 2 (the condition at 24_months) were not significant ($p > 0.05$) at the Cusio site while time-lag 3 (36_months) significantly explained the variability in the force values ($p < 0.05$, $F = 5.2$), as shown in Vergani et al. (2014a). In Averara, only time-lag 3 (30_months) was highly significant in explaining force variability (Table 5). Accordingly, the tensile force values of roots collected 30 months after felling were significantly different from those in the undisturbed condition, but there were no statistically significant differences between roots in undisturbed forest and roots collected one and two years after felling.

Table 5. Results of multiple regression models for Averara (∗ significant at 0.05, ∗∗ significant at 0.01; SE = standard error, p = p-value). The multiple regression equation is $Log(F) = a * log(D) + b * dummy2 + c * dummy3 + d * dummy4$.

Independent variable	**Coefficient**	**SE**	***t*-test**	***p* (>|*t*|)**	**Partial *F*-test**	***p* (>*F*)**
Diameter	1.68	0.08	21.76	<0.001**	441.46	<0.001**
6_months (dummy2)	0.0002	0.11	0.002	0.99	15.59	<0.001**
18_months (dummy3)	−0.17	0.12	−1.38	0.17	8.35	0.004**
30_months (dummy4)	−0.79	0.11	−6.94	<0.001**	48.12	<0.001**

3.3. Root cohesion

Total root cohesion was calculated for each soil layer under each of analyzed conditions as the sum of the basal and lateral cohesion values.

At Cusio, the values decreased from 20 kPa in the superficial layer to 5 kPa at 0.7 m (the maximum depth explored) in the undisturbed conditions, from 7 kPa to 2.5 kPa at 0.9 m after 12 months, from 6 kPa to 2 kPa at 1.1 m after 24 months, and from 3.5 kPa in the second soil layer to 0.9 kPa at 0.9 m after 36 months. A null value was returned after 60 months (Fig. 6). The average additional root cohesion values for a 70-cm reference profile of declined from 11 kPa at 0 months to 5 kPa after 12 months to 2 kPa after 36 months and to null after 60 months. The loss of additional root cohesion was nearly 60% in the first two years and an additional 20% in the third year (Vergani et al., 2014a); loss of cohesion was complete by the fifth year.

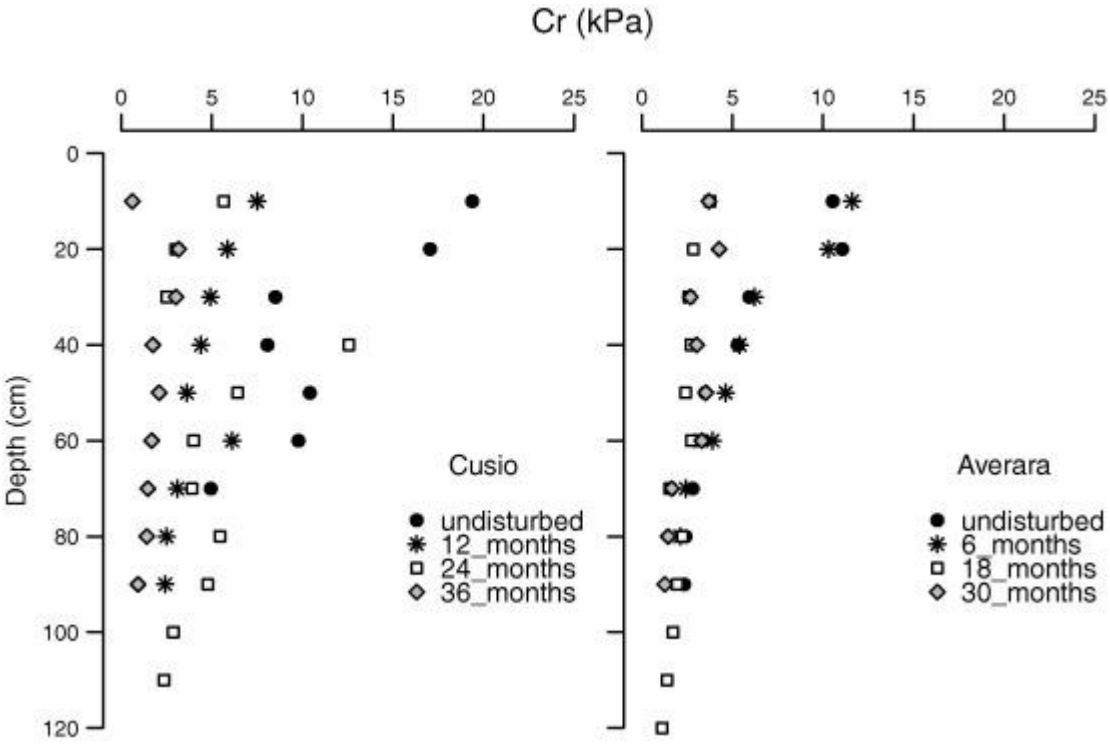

Fig. 6. Total root cohesion values for Cusio and Averara.

In Averara, values decreased from 11 kPa at the superficial layer to 2 kPa at 0.90 m under undisturbed conditions, from 12 kPa at the superficial layer to 2 kPa at 0.80 m after 6 months, from 4 kPa at the superficial layer to 1 kPa at 1.30 m after 18 months, from 4 kPa to 1 kPa at 0.90 m after 30 months and to null after 54 months (Fig. 6). The average values of additional root cohesion for a 90-cm reference profile passed from 5 kPa before falling to approximately 3 kPa in the first two years after felling (2.60 kPa and 3 kPa, respectively). The loss of additional root cohesion was on the order of 50% in the third year after felling and complete after five years.

3.4. Regrowth and vegetation dynamics

Table 6 shows the features of the natural regeneration within the surveyed gaps during the summer of 2014. Five years after logging, seedling density differed markedly between the two selected sites: 3.59 and 0.49 plantlets m−2 in Cusio and Averara, respectively. The prevailing species in the natural regeneration in both sites was silver fir followed by Norway spruce in Cusio; the latter species was rare in Averara. The regeneration of mountain pioneer species, such as rowan (Sorbus aucuparia), goat willow (Salix caprea) and

birch (Betula pendula), was also observed in both sites. Overall, most of the seedlings fell into the good and intermediate quality categories, but the advanced regeneration of conifer species (i.e., conifer seedlings aged >4 years) was absent in Averara and rare in Cusio, where most of the seedlings were of poor quality. In Cusio, the mean height of the fir seedlings ranged from 9.3 to 11.9 cm for ⩽4 years and plantlets >4 years old, respectively, while in Averara, regenerating firs aged ⩽4 years displayed a mean height of 7.5 cm. Spruce seedlings were between 12.5 and 14.4 cm in height in Cusio and 8.3 cm in Averara, in which most of the spruce seedlings were defined as of poor quality. The height of pioneer broadleaf species ranged from 15.9 to 40.3 cm. The average soil cover by the herbaceous and bush layers was approximately 82% in Cusio and approximately 70% in Averara; the most abundant species were grasses and blackberry (Rubus spp.).

Table 6. Number and height (H) of tree seedlings counted in the Cusio and Averara sampling plots by vegetative condition (good, intermediate, poor) and age (⩽4 years, >4 years) for conifer seedlings.

	Cusio					Averara				
Tree species	**Good (number)**	**Intermediate (number)**	**Poor (number)**	**Total (number)**	**Mean *H* (S.D.) (cm)**	**Good (number)**	**Intermediate (number)**	**Poor (number)**	**Total (number)**	**Mean *H* (S.D.) (cm)**
Abies alba ⩽ 4 years	112	73	45	230	9.3 (6.9)	3	7	14	34	7.5 (3.3)
Abies alba > 4 years	8	4	15	27	11.9 (6.3)				0	
Picea abies ⩽ 4 years	17	13	2	32	12.5(5.2)	2	2	0	4	8.3 (3.4)
Picea abies > 4 years	6	2	0	8	14.4 (4.5)				0	
Salix caprea	16	4	0	20	35.0 (16.7)	5	7	1	13	15.9 (9.3)
Betula pendula	8	1	0	9	40.3 (20.1)	6	2	0	8	35.0 (21.6)
Sorbus aucuparia	3	1	0	4	28.5 (14.5)				0	
Total	170	98	62	330		26	18	15	59	
# of seedling m^2[a]				3.59					0.49	

Values obtained by dividing the total number of seedlings by the total area sampled.

3.5. Slope stability

The FS values obtained for the three considered saturation conditions (25%, 50% and 75%) and a steepness range between 20° and 50° indicate that, in the undisturbed conditions at both sites, the probability of slope failure was always low (less than 10%) regardless of steepness and saturation level (Fig. 7). On the contrary, when additional root cohesion decreases or disappears completely, the probability of hillslope failure increases with steepness, especially when soil saturation increases. The failure probability exceeded 50% after 2–3 years under the following conditions:

− hillslope steepness greater than 36–38° and soil saturation of 25%,

− hillslope steepness greater than 31–32° and soil saturation of 50%,

− hillslope steepness greater than 24–26° and soil saturation of 75%.

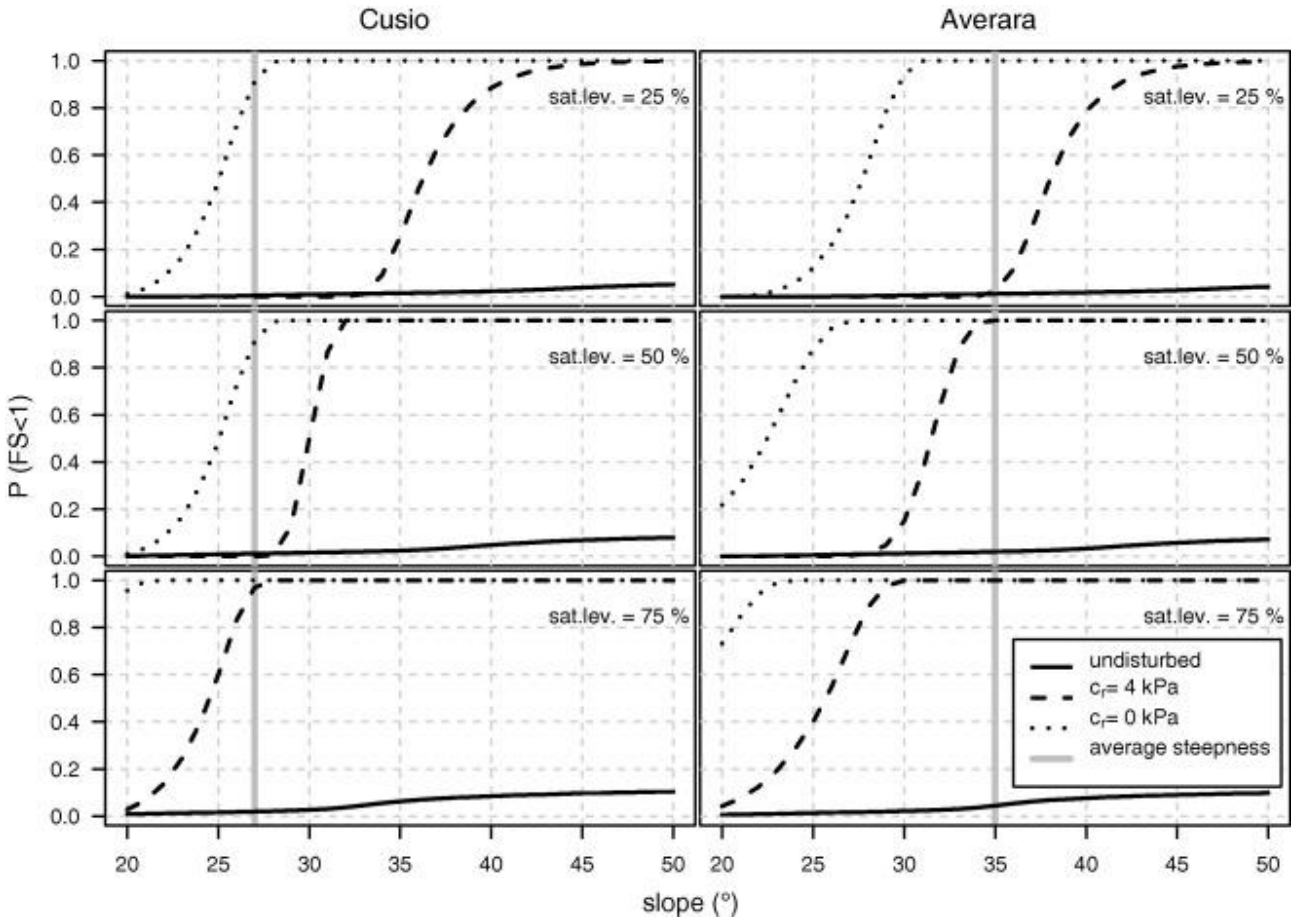

Fig. 7. Failure probability (FS < 1) as function of steepness for Cusio and Averara in undisturbed and cr = 0 conditions at three different saturation levels: (a) 25%, (b) 50% and (c) 75%.

The same probability of failure characterized hillslopes after about five years after felling, when root additional cohesion had completely decayed, under the following conditions:

− hillslope steepness greater than 25–28° and saturation of 25%,

− hillslope steepness greater than 20–23° and saturation of 50%.

Hillslopes are practically unstable regardless of their slope when saturation is 75%.

Considering the average steepness at the two study sites, it can be concluded that the probability of failure at Cusio is only high when additional root cohesion is completely decayed or soil saturation is high, and at Averara, a high failure probability occurs two or three years after felling when saturation is greater than 50%.

4. Discussion

Root density decreased with depth and time after felling, although the rate of decrease was not constant with time and depth. A decrease in the total number of roots with depth under undisturbed conditions has already been reported in the literature (Bischetti et al., 2005, Abdi et al., 2010, Genet et al., 2010, Mao et

al., 2012), and such a pattern was maintained in the study sites for the first 24–30 months after felling. After that, root number apparently decreased to zero after 54–60 months in both sites (Fig. 3).

The great reduction in the total number of roots that occurred in the third year can be explained by the reduction in fine roots, which agrees with the results of Zewdie et al. (2008). However, Silver and Miya (2001) found no significant differences in the decomposition rate of fine and medium (2–5 mm) roots.

The smoothing in the decreasing pattern of root distribution along the soil profile over time, which had been previously observed by Vergani et al. (2014a) in Cusio, was confirmed for Averara; after 30 months from felling, the pattern became uniform due to the degradation of the finer roots in the upper soil layers (Fig. 3). This is in agreement with the literature, in which it is well recognized that the decay rate of roots depends on several factors, such as root size and chemical composition (Silver and Miya, 2001, Fujimaki et al., 2008, Mao et al., 2011) and climatic and environmental factors (temperature, precipitation, oxygen and nutrient availability, etc.). Also, finer and shallower roots generally degrade faster than those that are thicker (Fahey et al., 1988, Fahey et al., 1991, King et al., 1997, Lin et al., 2011) and deeper (Ekelund et al., 2001, Ros et al., 2006). This is due to the activities of microbes and fungi, which are responsible for root deterioration and whose abundance and efficiency are known to strongly decrease with depth. Several studies have shown that most of the fine roots in the forest floor decompose during the first season after cutting, whereas fine roots in the mineral soil decompose more slowly (McClaugherty et al., 1984, Fahey et al., 1988, Fahey et al., 1991, King et al., 1997). Moreover, the rate of decay in terms of absolute and relative values varies greatly with environmental conditions (soil and climate) and root chemical composition (McClaugherty et al., 1984, King et al., 1997, Lin et al., 2011), so there might not be a regular process consisting of initial colonization followed by more rapid decomposition and, in turn, a slower phase of humification (Olajuyigbe et al., 2011), as observed in our study.

The decay process also affects root tensile resistance, which is generally expressed in terms of force at rupture and is dependent on root diameter. In the case of live roots, it is well known that the strength–diameter relationship follows a power law (i.e., Genet et al., 2010, Vergani et al., 2012), and the results obtained at Cusio (Vergani et al., 2014a) and Averara confirm that such a relationship is also valid in the case of roots sampled from felled trees, although the force values tend to spread out with time and move away from the live root line (Fig. 4). In addition, we observed that roots completely lost their mechanical strength in the fifth year after felling in both of our study sites.

Such dispersion of strength data can be ascribed to the mix of both degraded and intact roots in each diameter class that we observed in the soil profiles of our sites. On the one hand, the presence of both degraded and intact roots in each diameter class at the same time could be associated with the position of the roots within the soil profile (roots in the shallower soil layer should show a higher degradation rate), but on the other hand, it could also be interpreted as a stochastic process. Unfortunately, we did not mark the position of the tested roots in the soil profile, so this issue will be better explored in future research. The rate of degradation observed in our two cases partially agrees (Burroughs and Thomas, 1977, Ziemer and Swanston, 1977, O'Loughlin and Watson, 1979, O'Loughlin and Watson, 1981) and partially does not agree (Watson et al., 1997) with the available literature. However, such results have to be taken with caution because they are based on averaged values obtained from samples with different diameter distributions, which could strongly affect the estimated decay rate (Vergani et al., 2014a). More recently, Ammann et al. (2009), studying the root-rotting process in Norway spruce after felling and bark beetle attacks, observed a slower rate of decrease in tensile strength after felling (on the order of 60% of the original values after eight and ten years from cutting and 30% after twelve years).

As additional root cohesion, cr, is calculated from root strength, which is a function of root diameter, and root density, it followed the combination of the two variables. The results indicated that, after 6 months, root reinforcement was not reduced compared to the undisturbed condition, but afterwards, cr decreased

until it vanished in the fifth year (Fig. 6). As for the first two years, the tensile resistance of the roots was not significantly different compared to the values of the live roots (Fig. 4); cr decay was a result of the reduction in root density, especially in the upper 0.5 m of the soil profile (Fig. 6).

Studies of additional root cohesion decay are relatively rare in the literature and not particularly recent. The rates of decrease that we observed were more severe than those reported by Ziemer (1981) but consistent with reports from Sidle and Terry (1992). Ziemer (1981) estimated that about half of the original reinforcement was depleted within 2–3 years and two-thirds within 8 years; it was completely depleted within 25 years. Sidle and Terry (1992) reported relative decay curves for some North American forest species and showed that the additional root cohesion after 2–3 years from felling dropped by 30% for Pinus radiata, by approximately 35% for coastal Douglas fir, by approximately 50% for white fir-mixed conifer and Rocky Mountain Douglas fir, approximately 60% for Japanese cedar and approximately 80% for spruce-hemlock compared to the undisturbed condition.

As evident from the literature, the decay rate of both root density and root strength is affected by many local factors that should be seen as a function of soil and environmental factors.

Comparing our results with those from the literature (Fig. 8), it is evident that the decay rate we observed is greater than those observed for other species and environments, although there appears to be a logarithmic trend.

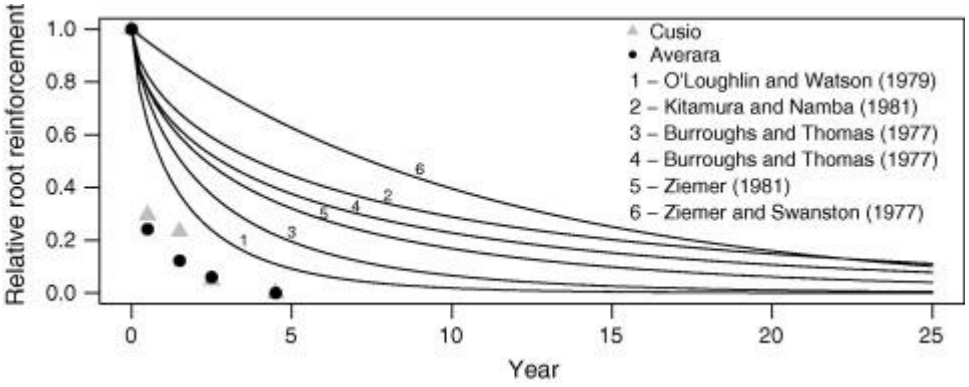

Fig. 8. Comparison between the relative reinforcement values obtained in our study and curves redrawn from the literature.

To account for forest regrowth, regeneration surveys began in the summer of 2014.

The regeneration process within the gaps appeared to be faster at Cusio than at Averara, which can be ascribed to many site- and stand-specific factors, such as seed availability, gap shape and the light conditions inside the gap, water availability, competition from herbs and shrubs, and ungulate pressure. In both sites, advanced regeneration was absent or negligible, which was probably due to the lack of light inhibiting the further development of seedlings as a consequence of high stand density. The poor vegetative conditions of many of the advanced Abies alba seedlings in Cusio may also be connected to longer exposure to browsing as silver fir is considered to be the most heavily browsed conifer in the Central European mountain forests (Häsler and Senn, 2012).

At both sites, Abies and Picea regeneration was more successful in the southern part of the gap (data not shown) where shading from the neighboring adult trees probably provides a more favorable light climate for these shade-tolerant species.

The slope stability analyses also revealed a dramatic increase in the probability of slope failure on less steep slopes with a low level of soil saturation (25%; Fig. 7). The root system could play a crucial role in stabilizing the hillslopes a few years after felling if steepness is not too relevant. In Cusio, which is less steep, a high

probability of failure occurs when the saturation level exceeds 75%, a quite severe hydrological condition. At Averara, where steepness is greater, a 50% saturation level causes slope instability.

Such results could be considered in contrast with the empirical evidence as, up to now, the hillslopes at both sites had not exhibited any instability. On the one hand, especially for Cusio, this could be explained by the fact that, in the last couple of years, the soil did not reach the level of saturation required for failure. On the other hand, the estimated FS values did not account for the role of forest regrowth and grass and bush colonization.

The results of the forest regeneration survey showed that emerging plants are not contributing significantly to soil stability due to scarce and shallow rooting, which was particularly evident at Averara where the probability of hillslope failure is greater than at Cusio. Bush colonization, in contrast, particularly by Rubus spp., provided significantly developed root systems that likely play a role in soil reinforcement.

From this perspective, two relevant aspects emerged (which are currently the focus of research): (i) the role and the rate of the regeneration process, especially where steepness is high and/or hydrological conditions may be critical and (ii) the role of soil colonization by grasses and bushes. Colonization by grasses and bushes may be fundamental to soil protection as the shrub layer benefits the soil properties before trees species emerge, but it could also be an obstacle to regeneration (Borghetti and Giannini, 2003) that affects slope stabilization over the medium and long term.

5. Conclusions

In this study, the deterioration of roots after felling in two silver fir-Norway spruce stands managed by gap-cutting in the Italian Alps was examined. The consequences of tree felling in terms of additional cohesion were estimated and incorporated into a probabilistic stability model to evaluate the effect of the practice of gap-cutting on slope stability.

The results presented here confirmed and expanded the findings of Vergani et al. (2014a). As with live roots, the tensile strength of roots sampled after tree cutting, in terms of rupture force, was related to root diameter by a power law relationship. At the same time, the force values showed increasing spread with time from cutting as a consequence of the presence of both decomposed and healthy roots.

Root deterioration did not affect root strength during the first two years after felling, but root strength reduction became statistically significant after 2–3 years. Five years after felling, the roots deteriorated and could not contribute to the reinforcement and mechanical stability of the soil.

Root cohesion, which is the combination of root strength and the distribution of root diameters, begins to decline as a consequence of root degradation between two and three years after cutting, and it drops to zero after five years. Such decay has important consequences for stability; without any contribution by forest root systems, hillslopes have a very high probability of failure that extends to gentle slopes and low levels of saturation. Emphasis must be placed on the rate of root decay in combination with the regeneration process by grass and bushes.

In the cases studied here, root decay was higher than that reported by Ziemer (1981) but was in agreement with Sidle and Terry (1992). The resulting net reinforcement curve could be anticipated with a lower minimum and a higher probability of hillslope failure.

When these conditions are likely to occur, gap size should be decreased to reduce site exposure to landslides, particularly in areas with higher inclines. As the ratio between the lateral and basal sliding

surfaces is a key parameter in determining additional root cohesion, the gap should be shaped to maximize the ratio by aligning the main gap dimensions with the contour lines.

In a simulation study concerning the ability of forest stands to protect human activities against natural hazards, Cordonnier et al. (2008) concluded that gap-oriented silviculture may be a good option for combining forest regeneration with protection efficiency in mountain regions. From a broader perspective, this practice couples the preservation of site conditions and their ecological and economic benefits, as introduced by close-to-nature silviculture (Schütz, 1999). In addition, closed stands could be progressively thinned prior to gap creation to stimulate the presence of advanced regeneration, which contributes to slope protection immediately after the canopy opening. In fact, shade-tolerant species can grow and survive for considerable periods in low light (Wright et al., 2000), and the role of this advanced growth in forest regeneration has been already emphasized (Greene et al., 2002; Kuuluvainen, 2002).

Finally, this work suggests some areas for future research into slope stabilization (besides prolonging the time span after felling and extending investigation to other species and environments, which are driving factors in root decomposition), with particular reference to the rate and role of forest regrowth and its relationship with pioneer vegetation.

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